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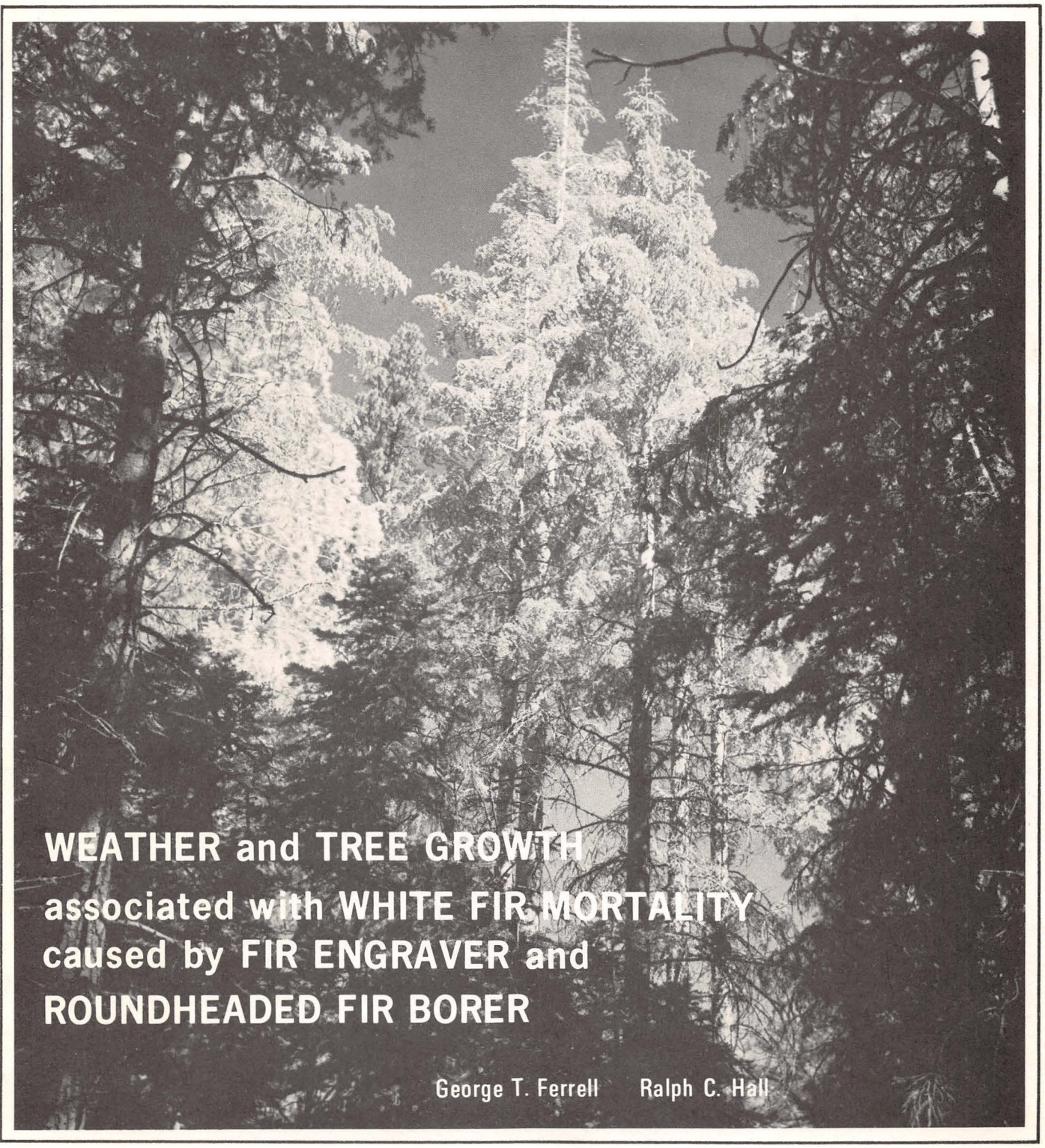

WEATHER and TREE GROWTH associated with WHITE FIR MORTALITY caused by FIR ENGRAVER and ROUNDHEADED FIR BORER

George T. Ferrell Ralph C. Hall

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Cover photo: White fir trees, *center,* are faded following attack by fir engraver.

SUMMARY

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Oxford: 174.7 *Abies concolor:* 453:423 + 453–145.7x19.92 *Scolytus ventralis*–174.7 *Abies concolor* + 453–147.19.88 *Tetropium abietis* –174.7 *Abies concolor.*

Retrieval Terms: Abies concolor; Scolytus ventralis; Tetropium abietis; insect attack; mortality; weather; precipitation; radial growth; multivariate analysis.

To assess their value as predictors, fluctuations in growth of white fir (*Abies concolor*) and weather patterns in the Hat Creek region of northeastern California were compared with trends in tree mortality caused by fir engraver (*Scolytus ventralis* Lec.) and roundheaded fir borer (*Tetropium abietis* Fall) beetles. The volume of white fir sawtimber killed annually by the beetles was obtained from yearly surveys of 22 20-acre (8-ha) plots from 1944 to 1954. The stems of suppressed, intermediate, and dominant white fir growing on these plots were bored in 1972 and annual ring widths for these years were measured. To improve comparability of growth measurements in fir growing under a variety of site and stand conditions, two annual growth indexes were calculated: (a) growth index (departure from normal), and (b) growth sensitivity (rate of change). Yearly means of these indexes were obtained for all sample fir, and fir in each crown class, on the plots.

Between-years variation in fir mortality, and in the growth indexes for the dominant, intermediate, and all sample fir was significant compared to within-year (between plots) variation. These were averaged for all plots to obtain regional measures of annual mortality and growth. Because trends in the growth of suppressed fir were not statistically significant, these trends were excluded from further analysis.

Seasonal and annual precipitation and mean air temperatures for the study period were obtained from local weather records. Each year's weather and growth were averaged with those of the previous 1 and 2 years to include previous conditions. The influence of previous and current weather and growth upon the average volume of fir killed annually was examined by stepwise multivariate regression. Weather and growth submodels were developed and variables significant within each submodel were combined to form a final predictive model.

The weather submodel statistically explained 95 percent of the variation in fir mortality, while the growth submodel explained 51 percent. The addition of fir growth to the weather variables failed to increase the amount of variation explained by the final model. Fir mortality increased in years when one or more of the following occurred: (a) radial growth of fir during the current and previous 2 years declined an average of 2.5 percent per year; (b) precipitation during the current and preceding year averaged 11 percent below normal; and (c) the current year's spring precipitation averaged 32 percent below normal. Trends in pine mortality were compared to those in fir on the plots and were found to be similar during the study period.

Regional levels of fir mortality due to the beetles were primarily related to regional, year-to-year fluctuations in the radial growth of both dominant and intermediate fir. This interpretation is based on the finding that indexes of the combined crown classes were superior to those of either crown class by itself and indexes of suppressed trees had been excluded earlier in the analysis.

The results suggest that fir mortality caused by the subcortical insects increases during periods of drought and reduced fir growth, probably because of decreased resistance of fir to the beetles.

White fir (*Abies concolor* [Gord. & Glend.] Lindl.) stands in Western North America periodically suffer extensive tree mortality caused by outbreaks of the fir engraver bark beetle (*Scolytus ventralis* Lec.). The cambial zone of the boles infested by *S. ventralis* is also colonized by the roundheaded fir borer (*Tetropium abietis* Fall) (Struble 1957). Only a few of these outbreaks have been related to underlying environmental factors, such as drought or host tree defoliation (Stevens 1971, Wickman 1963). The dearth of long-term, quantitative estimates of the population levels of these insects and the associated fir mortality has hampered better understanding of factors influencing these outbreaks.

As an index to past levels of fir mortality caused by the fir engraver, year-to-year fluctuations in the abundance of old attack scars embedded in annual rings of living and recently killed white fir were studied (Ferrell 1973). The year of attack was readily determined by noting the annual ring in which the scar was embedded. The scars form a semipermanent record of at least a portion of the interaction between the insect population and the host trees over long periods in the past. Scars were more abundant in annual rings formed in years when precipitation and fir growth during the current and preceding 1 to 2 years were subnormal—especially when these conditions were contemporaneous with logging operations within the stand. Fir killed by the beetles showed rapidly increasing frequencies of scars in the narrow annual rings formed in the last few years before the trees had succumbed. The results agreed with those of Felix and others (1971), who found increased frequencies of fir engraver scars in annual rings formed in years of drought in the upper boles of white fir infected by true mistletoe.

During a study of pine mortality caused by bark beetles from 1938 to 1954 (Hall 1958), records (unpublished) were kept of annual fir mortality caused by subcortical insects on cruise plots 30 miles to the north of the scar study plots. Forest insect surveys had reported that fir engraver damage was generally high in 1939-40 and low in 1948 throughout the region embracing both the scar and mortality plots.[1] This fact suggests the possibility that trends in fir engraver populations on both study areas might be similar. The finding that annual levels of fir mortality were directly correlated with scar abundance over a 15-year period lent validity to the use of the scars as an index to past levels of fir mortality. Trends in the scars and the fir mortality were similar during 12 of these 15 years, but were dissimilar during the other 3 years. These departures may have resulted from sampling error or other variables not studied.

This paper reports a study of multiple regression analysis of the association of weather and tree growth with white fir mortality caused by the fir engraver and roundheaded fir borer beetles in northern California.

METHODS

Fir Mortality

A total of 38 plots, each 20 acres (8 ha), had been established in 1938-39 in forest stands growing in the Pit River drainage within a 20-mile (32 km) radius to the north, west, and south of Burney, Shasta County, California (Hall 1958). Because 16 plots had little or no white fir sawtimber, they were excluded from the present study. The other 22 plots were in mixed conifer stands varying in amount (300 to 42,240 bd. ft./acre or 4 to 591 m^3/ha) and in percentage (1.2 to 68.9 percent) of white fir in the sawtimber volume. The plots also varied in elevation (3300 to 6600 ft. or 1006 to 2012 m) and logging history (virgin to cutover). They probably represented a reasonable cross-section of stands holding white fir in the region.

Tree mortality from 1944 to 1954 was determined by annual 100 percent surveys in late fall or the following spring, when currently infested fir attacked by subcortical insects the preceding summer usually had faded foliage. After the diameter at breast height (d.

[1] Salman, K. A. 1939. *Reconnaissance of west side infestation conditions. Season of 1939.* Engen, E. T. 1950. *Forest insect survey, Lassen National Forest and adjacent private lands. Seasons of 1949 and 1950.* (Unpublished reports on file at the Pacific Southwest Forest and Range Experiment Station, Berkeley, California.)

b. h.) and the height of each dying fir greater than 11 inches (28 cm) d. b. h. were recorded, the bark was chopped into at breast height. Any subcortical insects found were identified from their gallery patterns. Previously unsampled, recently killed fir from which the beetles had already emerged were counted as mortality of the previous year. These trees, evidently infested in late summer, had not faded at the time of the fall survey and therefore had escaped detection in the year of infestation. The merchantable volume of each dead tree was obtained from local volume tables.

Fir engravers or roundheaded fir borers were found in all but a few of the fir sampled. Struble [2] had dissected a representative sample of white fir killed by subcortical insects in mixed conifer stands in the central Sierra Nevada. He found that with few exceptions the upper boles of the larger fir had been infested by fir engraver whereas fir borer had colonized the thick-barked lower boles. In the present study, we thought it likely that sampling at breast height would often fail to reveal the presence of fir engraver—even though both insects had infested the tree. Because these two beetles frequently are found together in dying fir, we did not try to separate them for this analysis.

Fir Growth

Radial growth of white fir during the study period was sampled by boring the stems of nine living trees at breast height on each plot in August 1972. Radial growth in the basal portion of the stem is not only readily accessible for sampling, but also is known to be sensitive to weather variation (Fritts 1966). To study the influence of the tree's crown class upon the usefulness of its growth as a predictor of beetle mortality trends, we obtained an increment core from three suppressed, three intermediate, and three dominant fir trees on each plot. Within each crown class, individual trees and the particular stem radius bored were randomly selected. The cores were stored at room temperature for 3 months before we measured the width (± 0.01 mm) of each annual ring formed during the study period.

Weather

Monthly precipitation and mean air temperature recorded at Hat Creek Powerhouse No. 1 from October 1941 to September 1954 were obtained from annual summaries of California weather published by the U. S. Weather Bureau. The weather station was at a lower elevation (3010 feet or 917 m) than the mortality plots and stands containing fir in the region. We recognized that weather at the plots would vary according to topography and elevation and would differ from that recorded at Hat Creek Powerhouse. Annual and seasonal precipitation at the station was compared with that in the fir zone by means of rain gauges set up on four widely scattered mortality plots ranging in elevation from 3300 to 5300 feet (1006 to 1615 m). Precipitation was recorded from 1939-44 on two of the plots, and through 1948 on the other two.

DATA ANALYSIS

Fir Mortality

Total mortality caused by fir engraver and roundheaded fir borer on the plots (1944-54) was 111 fir trees (>11 inches or 28 cm d.b.h.) containing 188,620 bd. ft. (1068 m^3) of merchantable sawtimber volume. Fir borer was found subcortically at breast height in 80, fir engraver in 29, and both species in two of these trees. The dead fir trees averaged 30 inches (76 cm) in d.b.h. and 1700 bd. ft. (9.6. m^3) in volume, but ranged from 12 to 58 inches (30 to 147 cm) in d.b.h. and 40 to 6850 bd. ft. (0.2 to 38.8 m^3) in volume. More than half the trees were less than 28 inches (71 cm) d.b.h. and 1000 bd. ft. (5.7 m^3) in volume.

Average fir mortality caused by the beetles on the plots fluctuated from a high of 85.18 bd. ft./acre (1.19 m^3/ha) in 1954 to a low of 0.79 bd. ft./ acre (0.01 m^3/ha) in 1948. In all years between-plot variation was high, with no mortality on some plots even in years when average mortality was highest (*table 1*). The variance-to-mean ratio was high, increasing disproportionately with size of the mean, implying that the mortality was distributed among the plots in non-normal, clumped fashion. To determine if the variation between years was more significant than that among plots, we had to transform the mortalities mathematically. Such a transformation was needed to

[2] Struble, George R. 1931. *The fir engraver beetle and associated insects in white fir, season of 1930.* (Unpublished report on file, Pacific Southwest Forest and Range Experiment Station, Berkeley, California.)

Table 1—*White fir sawtimber mortality caused by fir engraver and roundheaded fir borer on 22 20-acre (8-ha) plots in northeastern California, 1944-54*

Year	Average	Range
	bd.ft./acre (m^3/ha)	
1944	25.66 (0.36)	0-339.00 (0-4.7)
1945	84.75 (1.19)	0-408.50 (0-5.7)
1946	72.29 (1.01)	0-588.00 (0-8.2)
1947	50.84 (0.71)	0-708.50 (0-9.9)
1948	.79 (0.01)	0- 17.50 (0-0.2)
1949	51.27 (0.71)	0-432.00 (0-6.0)
1950	35.43 (0.50)	0-525.00 (0-7.3)
1951	11.82 (0.17)	0-215.50 (0-3.0)
1952	5.11 (0.07)	0-112.50 (0-1.6)
1953	16.91 (0.24)	0-272.00 (0-3.8)
1954	85.18 (1.19)	0-409.00 (0-5.7)

satisfy the assumptions underlying analysis of variance (Steel and Torrie 1960). The transformation used, $1/(x + 1)^{-0.1}$, x = annual plot mortality (bd. ft./acre), effectively reduced the mean-variance correlation to zero, implying the variance had been stabilized. Analysis of the transformed mortalities indicated that the variation between years was significant ($F = 3.57$, $df = 10,231$, $p<.01$). Therefore we used the mean volume per acre of fir killed annually on the plots as the dependent variable to estimate regional level of fir mortality caused by the beetles. Correlation between mean mortality in any year with that occurring the previous year was not significantly different from zero (serial $r = 0.14$), implying that the previous year's mortality had little influence, and we excluded it as an independent variable in the regressions.

Fir Growth

The width of annual rings formed during successive years at a given height in a tree bole is affected by the availability of nutrients and moisture as influenced by spatial and temporal variations in conditions both internal and external to the tree (Fritts 1966). For the analysis, we intended growth to be an indirect measure of many of these influences for which records were not available. We sought to relate year-to-year variations in average levels of growth to those of fir mortality within the region studied. To establish these regional growth variations, the radial growth of many white fir differing in age, size, crown class, growing site, and surrounding forest stand was measured.

To increase comparability of growth measurements and to isolate for analysis year-to-year regional fluctuations in growth due to such conditions as variable weather, two growth indices were calculated by the computer program INDXA (Fritts 1966):

Growth index was calculated by fitting a least-squares regression line with negative, zero, or positive slope to each tree's ring width series. Plotting the ring width series of a subsample of the trees indicated curvilinearity could be ignored because the series being studied was short. Each year's growth index was calculated by dividing the observed ring width by the value estimated by the regression line. Growth indexes of unity represent normal, <1 subnormal, and >1 supranormal growth.

Growth sensitivity was calculated by dividing the signed difference between the current (RW_2) and preceding (RW_1) year's ring widths by the average ring width for the 2 years ($RW_2-RW_1/\overline{RW}$). This index defined the rate of decline or increase in radial growth between any two successive years. It was standardized by being expressed as a proportion of the average ring width for the period, (that is, a sensitivity of -0.03 denoted a 3 percent decrease in standardized radial growth between two successive years). Summaries including trees in each, and in all, of the crown classes from each plot were then computed, yielding yearly means and standard errors of the indexes.

To screen the growth variables for significant, year-to-year variation, F tests were used to analyze the annual plot values of the mean indexes to determine if between-years variation was statistically significant compared to within-years (between plots) variation. The F ratios obtained for growth index (6.76) and sensitivity (5.27) for the combined crown classes, sensitivity of the dominants (4.98), and growth index of the intermediates (3.32) were all significant ($df = 12,273$, $p<.01$). We then used yearly averages of these on all plots to construct independent variables expressing regional host tree growth in the regression analysis. Because between-year variation in both growth indexes for suppressed fir was not significant, we excluded them from further analysis.

Weather

The annual weather pattern in the region consists of a distinct wet (usually October to June) and dry season. About 80 percent of the total precipitation occurs in the six winter months, much of it falling as snow. The summer months are normally dry and warm, with precipitation limited to scattered local

thundershowers. Thus tree growth in spring and early summer is largely dependent upon soil storage of winter precipitation.

We considered total precipitation and mean air temperature occurring from the preceding October through the current September to represent both the direct and indirect influences of annual weather upon fir mortality caused by the insects during the current (i^{th}) year (i = 1944-54).

Different developmental stages of the insects occur seasonally. Both insect species studied overwinter as larvae and pupate in spring, with adult emergence, flight, and host colonization occurring primarily in summer. The influence of seasonal weather upon the level of fir mortality caused by the insects was assessed by subdividing the year's weather pattern into that occurring in winter (October-March), spring (April-June), and summer (July-September).

Comparison of weather at Hat Creek Powerhouse with that on the mortality plots showed that mean precipitation on the plots exceeded that at Hat Creek at all seasons, but the amount of excess varied widely from plot to plot. These precipitation excesses ranged from 4.5 to 20 inches (11.4 to 50.8 cm) in winter, 1 to 8 inches (2.5 to 20.3 cm) in spring, 3 to 7 inches (7.6 to 17.8 cm) in summer, and 4.5 to 30 inches (11.4 to 76.2 cm) annually. However, correlation of annual and seasonal precipitations at Hat Creek Powerhouse with those recorded on the mortality plots indicated similar weather patterns. The ranges of correlation coefficients obtained were 0.97 to 0.78 for winter, 0.93 to 0.63 for spring, 0.96 to 0.42 for summer, and 0.97 to 0.71 for annual precipitation. Both seasonally and annually the strength of the correlation decreased as distance and elevation change increased between the plot and Hat Creek Powerhouse. We concluded that weather patterns at Hat Creek Powerhouse sufficiently reflected general weather pattern over the region studied for this analysis.

Previous Growth and Weather

To study the influence of previous growth and weather conditions upon fluctuations in fir mortality caused by the beetles, we combined data on the current (i^{th}) year with data of up to two preceding (j^{th}) years ($X_{i,j}$ j = 1,2) and averaged these values. Although we realized that such averages might only approximate the influence of previous conditions upon the current level of insect-induced fir mortality, such averages have been used in similar studies (Felix and others 1971, McManus and Giese 1968) in the absence of known relationships.

Multivariate Regression

Stepwise multivariate regression was used to examine the usefulness of previous and current fir growth and weather (independent variables) in explaining yearly variations in fir mortality caused by the beetles (dependent variable). The independent variables were assumed to be related to the dependent variable in a linear, additive model. Nonlinearity (single peaks or depressions) in the relationships between the dependent and independent variables was at least partially allowed for by including both the independent variables and their squares in the regression. We do not mean to imply necessarily that the real relationships are accurately described by the variables being introduced into such a model in this manner, but only that such would be a satisfactory first approximation.

Computation of the regression coefficients and associated statistics (R^2, t^2, standard error of estimate) was performed by a computer program (RAFL) written by personnel of the Pacific Southwest Forest and Range Experiment Station. The program included a stepping option by which the independent variables could be added one at a time in order of descending efficiency in reducing the unexplained variance in fir mortality (t^2 criterion).

Initially only the growth variables were included in the computations. The variables statistically explaining significant amounts of the variance in mortality (denoted by the coefficient of determination, R^2) comprised a growth submodel. Similar analysis of weather variables yielded a weather submodel. Independent variables significant in each submodel were then combined in a further stepwise analysis. This combination yielded significant variables in the final predictive model. This method allowed the relative value of host tree growth and weather to be compared individually or in combination in explaining year-to-year variation in regional fir mortality caused by the insects.

RESULTS

Significant Variables

Tree growth and weather variables explained significant amounts of variation in annual fir mortality caused by fir engraver and fir borer from 1944 to 1954 (*table 2*). The only variable significant in the growth submodel was the mean sensitivity of all fir sampled, averaged over the current and two preceding years ($MS_{i,2}$). This variable explained 51 percent of the mortality variation ($F = 9.24$, $df = 1, 10$, $p<.05$).

Three variables were significant in the weather submodel; together they explained 95 percent of the mortality variation ($F = 41.28$, $df = 3, 10$, $p<.01$). The most important weather variable was the average precipitation during the current and preceding year ($Precip._{i,1}$), which explained about 73 percent of the mortality variation. The second most important variable was the current year's spring precipitation ($Spr. precip._i$), which when included in the model increased the amount of mortality variation explained to 85 percent. The last significant variable added to the weather submodel was the square of the mean air temperature during the current and preceding spring ($Spr. temp._{i,1}^2$), indicating a curvilinear relationship with fir mortality.

Table 2—*Tree growth and weather factors influencing the mean volume of white fir (bd. ft./acre) killed annually by* Tetropium abietis *and* Scolytus ventralis *on 22 plots near Burney, California, 1944-54*

Independent variables[1]	Description	Percent variation in timber loss explained ($100 R^2$)
Tree Growth:		
$MS_{i,2}$	Mean sensitivity, current and two preceding years	50.65*
Weather:		
$Prec._{i,1}$	Average total precipitation during current and preceding year	72.61
$+Spr. precip._i$	Spring precipitation, current year	85.11
$+(Spr. temp._{i,1})^2$	Mean spring temperature, current and preceding year squared	94.65**

* $F = 9.24$, significant at 5 percent level.

** $F = 41.28$, significant at 1 percent level.

[1] Added in order of descending efficiency in explaining variation in the annual timber loss. Each variable was significant at the 5 percent level (t^2 criterion).

Combining the significant growth and weather variables into a further stepwise regression analysis led to the addition of the significant weather variables and to the exclusion of the growth variable owing to lack of significance in the final model. Not unexpectedly we found much overlapping between the influences of fir growth and weather upon the fir mortality, with weather variables supplanting growth variables because of their greater efficiency (higher t^2) in explaining the mortality variation. Comparison of scatter diagrams and regression equations for the most important growth and weather variables reinforced this finding (*fig. 1*). The superiority of precipitation in predicting fir mortality was evident from the lower scattering of the observed tree mortalities about the regression line, yielding a higher R^2 and a lower standard error of the estimate ($S_{y \cdot x}$) compared to the regression based on the growth variable.

The multivariate regression equation for the final model was

$$Y = 427.55 - 8.90X_1 - 5.42X_2 - .06X_3$$

in which

Y = Mean volume of fir sawtimber killed annually by fir engraver and fir borer (bd. ft./acre)

X_1 = Mean precipitation during current and previous years (inches)

X_2 = Spring precipitation, current year (inches)

X_3 = Mean air temperature during the current and preceding spring, squared (°F)

The coefficient of determination (R^2) was 0.947, and the standard error of estimate was 8.58 bd. ft./acre.

Increased Fir Mortality

The model relates increased fir mortality to years with one or more of the following: (a) decreased mean precipitation during the current and preceding year, (b) decreased precipitation during the current spring, and to a lesser extent, (c) decreased mean temperature during the current and previous spring (*fig. 2*).

The higher levels of fir mortality occurring in the years 1945-7, 1949-50, and 1954 were associated with years of deficient annual or spring precipitation or both. The effect of current spring precipitation in modifying the influence of previous and current annual precipitation upon the level of current mortality was evident in trends between 1946 and 1947. Annual precipitation was low in 1946 and declined further

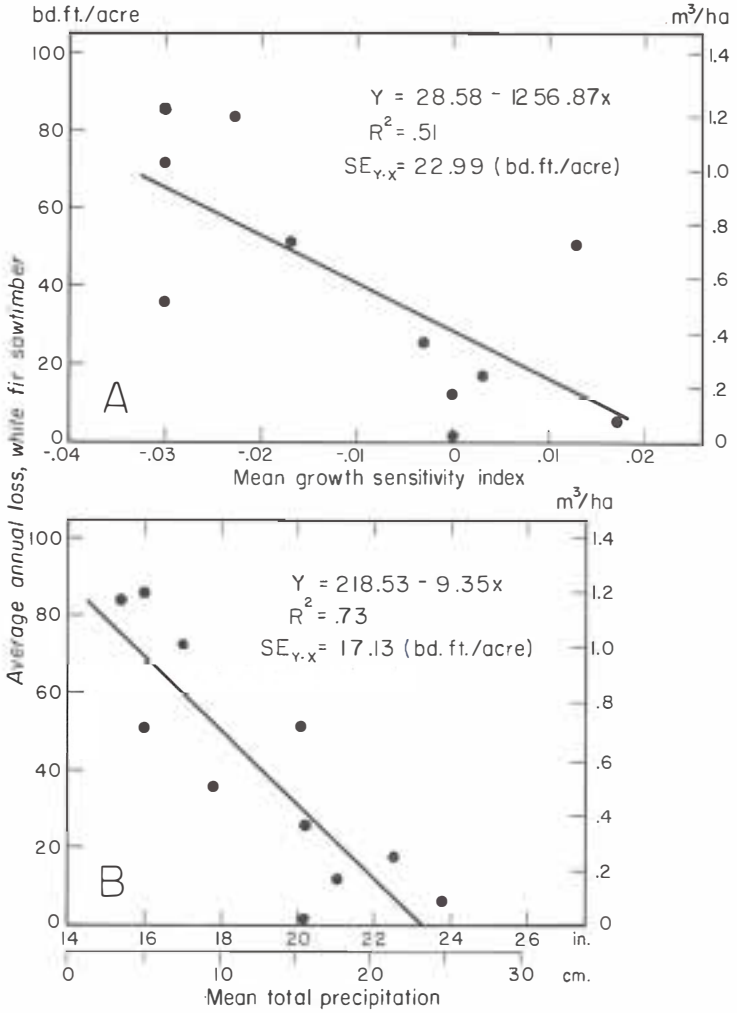

Figure 1—The average volume of white fir sawtimber killed annually by fir engraver and roundheaded fir borer declined, *A*, as the mean growth sensitivity—an index of the radial growth in fir for the current and two preceding years—increased; and *B*, as the total precipitation for the current and previous years increased.

in 1947, but fir mortality continued to decrease in 1947—evidently in response to a twofold increase in spring precipitation in 1947 over 1946. The low mortality and high annual precipitation in 1948 were both attributable to an unusually wet spring in that year. The lesser significance of spring temperature in the model was not apparent from trends in the variables, but was probably associated with the inverse relation of spring temperature to spring precipitation.

Higher levels of fir mortality (>40 bd. ft./acre of 0.56 m^3/ha) occurred in five of the years studied, when precipitation during the current and preceding year averaged 16.90 inches (42.93 cm) or 11 percent less than the average for the study period (19.09 inches or 48.49 cm) and spring precipitation averaged 2.60 inches or 6.60 cm), or 32 percent below the period average (3.81 inches or 9.68 cm). Mortality exceeding 40 bd. ft./acre (.56m^3/ha) also occurred in 4 years, when the average decline in the radial growth of fir during the current and preceding 2 years was 2.5 percent per year (mean sensitivity = -0.025). An exception to this pattern was 1947, when mortality was declining but still averaged 50 bd. ft./acre (0.70 m^3/ha) while radial growth of fir during the current and preceding 2 years increased by an average of 1.3 percent per year. This relatively high mortality during a period of increasing host tree growth was evidently due to the deficient annual precipitation of 1947.

In an earlier study, Hall (1958) analyzed the influence of current weather and soil moisture on volume of pine sawtimber killed annually by *Dendroctonus* and *Ips* bark beetles on 38 plots. He found increased pine mortality associated with dry hot springs and with low soil moisture contents in mid-July. In comparing his findings with ours from 22 of the same 38 plots, we noted that pine losses were higher, but mortality trends of the two tree species were similar during most of the years 1942 to 1950 (*fig. 3*).

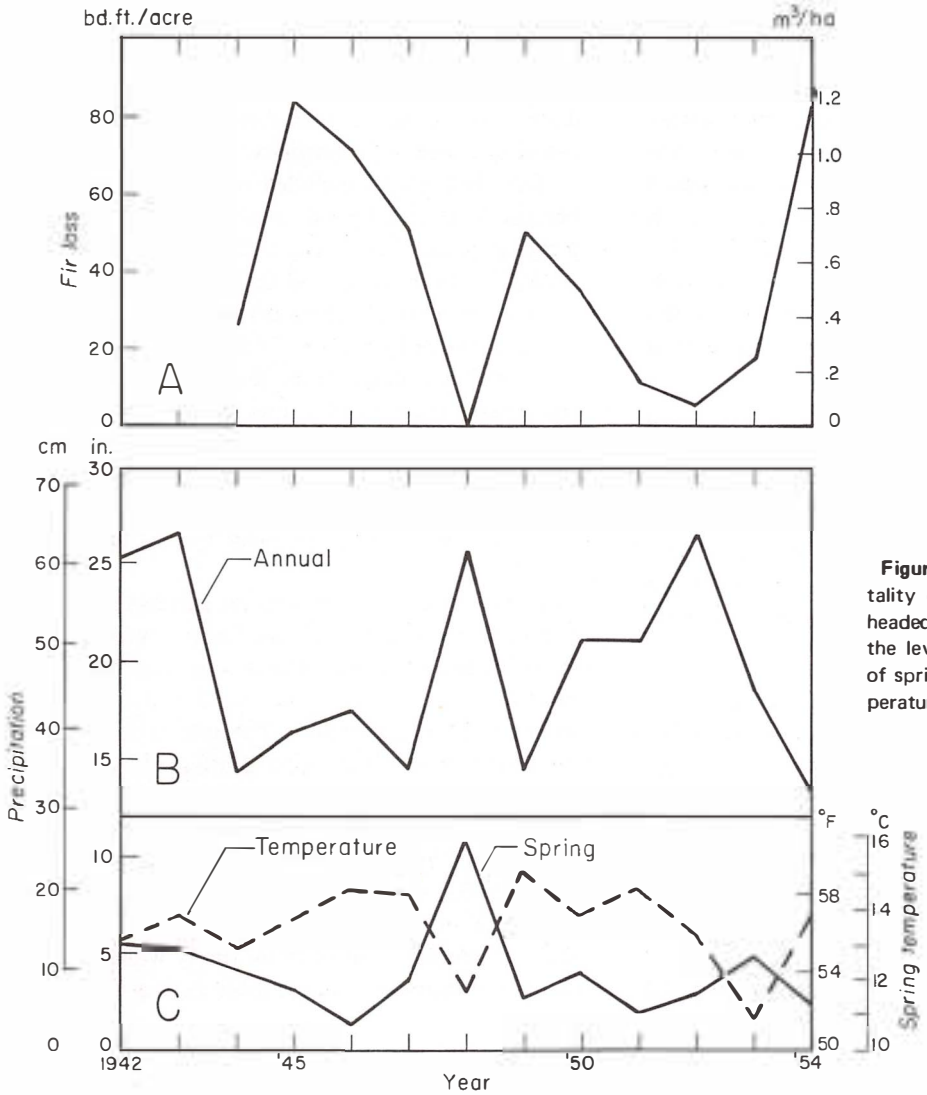

Figure 2—The annual level of fir mortality caused by fir engraver and roundheaded fir borer, *A*, varied inversely with the levels of total precipitation, *B*, and of spring precipitation and mean air temperature, *C*.

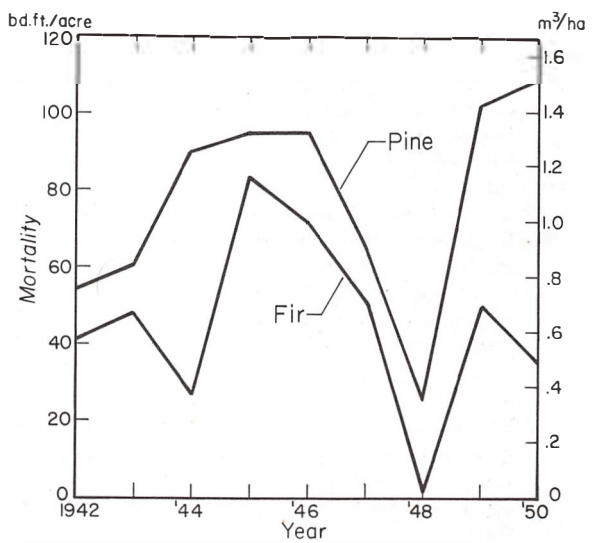

Figure 3—Trends in the mean annual mortality of white fir and pine caused by subcortical insects on the study plots were similar during the years 1942 to 1950.

CONCLUSIONS

White fir mortality increased in years when current and previous precipitation and fir growth were subnormal or declining. This same association was found in the abundance of fir engraver attack scars in both living and recently killed fir (Felix and others 1971, Ferrell 1973). Annual precipitation was a more significant variable than seasonal precipitation. Air temperatures were, by themselves, of minor importance in the analysis.

Higher fir mortality was more closely associated with periods of years with declining radial growth (negative growth sensitivity) than with subnormal radial growth (growth index less than one). Decreased radial growth, even though still above the normal predicted from growth patterns of fir in the region, is evidently a more sensitive indicator of impending increases in beetle-caused fir mortality.

The radial growth of fir in all crown classes was more closely associated with annual levels of regional fir mortality than with the growth of any single crown class analyzed. This relationship corresponds with the observed wide variability in the size (and crown class) of fir killed by the insects. As year-to-year fluctuation in the growth of suppressed fir was not significant, it probably contributed little to the importance of the growth of the combined crown classes in the model. Drought adversely affecting the growth of fir in primarily the dominant and intermediate crown classes is probably required to cause regional increases in fir mortality.

The final model included only weather variables because host tree growth was of lesser value in explaining fluctuations in regional levels of fir mortality caused by fir engraver and fir borer. This study supports what other investigators have established: that weather can influence the fir engraver both directly, i.e., larval mortality from low winter temperature (Berryman 1970), and indirectly through alteration of host tree physiology (Berryman 1972, Felix and others 1971), although many of the exact pathways by which weather influences trends in fir mortality caused by the beetles probably remain to be elucidated.

In this study, general weather patterns adequately explained year-to-year fluctuations in average levels of beetle-caused fir mortality in a forested region. But mortality varied widely among the study plots in most of the years studied. The interaction between the host tree and insect pest is affected by a variety of factors, including weather, site, and stand conditions. Some have already been reported; for example, defoliation (Wickman 1963), root diseases (Stark and Cobb 1969), mistletoe (Felix and others 1971), and logging (Ferrell 1973). The development of models that can predict levels of fir mortality within a particular forest stand will require more extensive investigation.

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1975. **Weather and tree growth associated with white fir mortality caused by fir engraver and roundheaded fir borer.** USDA Forest Serv. Res. Paper PSW-109, 11 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Multivariate regression analysis was used to explore the relationship of weather and tree growth to the average volume of *Abies concolor* sawtimber killed annually by fir engraver (*Scolytus ventralis* Lec.) and roundheaded fir borer (*Tetropium abietis* Fall) beetles. Data for the years 1944 to 1954 from 22 plots in northern California showed that white fir mortality increased in years when (a) fir radial growth during the current and previous 2 years declined an average of 2.5 percent per year, (b) precipitation during the current and previous years averaged 11 percent below normal, or (c) spring precipitation averaged 32 percent below normal. Levels of mortality were related chiefly to regional fluctuations in radial growth of dominant and intermediate fir.

Oxford: 174.7 *Abies concolor:*453:423 + 453–145.7x19.92 *Scolytus ventralis*–174.7 *Abies concolor* + 453–147.19.88 *Tetropium abietis*– 174.7 *Abies concolor.*

Retrieval Terms: Abies concolor; Scolytus ventralis; Tetropium abietis; insect attack; mortality; weather; precipitation; radial growth; multivariate analysis.

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